UUV DYNAMIC CONTROL FOR MINEHUNTING WITH SYNTHETIC APERTURE SONAR

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Abstract

This paper discusses the demands that integration of a Synthetic Aperture Sonar poses for the dynamic control of a small Unmanned Underwater Vehicle, and how these requirements are being met for the new Bluefin12. In particular, analysis and simulation of vehicle response to wave action in shallow water and steady current across the direction of travel is presented. Combined with modeling of sonar response, this leads to performance requirements for the sensors and actuators, minimum update rate and maximum latency for communication, predictions for the selected control strategy, and sensor fusion algorithms. The hardware implementation is described and preliminary data of the system performance presented.

Introduction

In the mission-critical metric of area coverage rate (ACR), Synthetic Aperture Sonar (SAS) systems hold the promise of much greater performance than existing real aperture systems. SAS in combination with Unmanned Underwater Vehicles (UUV) can produce high quality scans of the seafloor very efficiently. Thus, an effective, scalable, and covert Mine Countermeasure capability can be realized that keeps humans out of harms way. However, the longer range, higher resolution SAS sensor systems impose demanding requirements for UUV steadiness and dynamic control, more so for certain degrees of freedom. Meeting these requirements in the presence of shallow water fluid disturbances is particularly challenging. SAS motion steadiness requirements lead to derived requirements for several UUV subsystems – notably the autopilot, control surfaces, actuators and motion measurement instrumentation. Bluefin's new model, Bluefin12, is being designed to meet these unique requirements.

Figure 1 shows an preliminary outline of the vehicle in its Search-Classify-Map (SCM) configuration, where a SAS developed by Penn State University's Applied Research Lab and NAVSEA's Coastal Systems Station is combined with the Dual Frequency Identification Sonar (DIDSON) from University of Washington's Applied Physic Lab, to provide a gap-free swath of the sea floor.

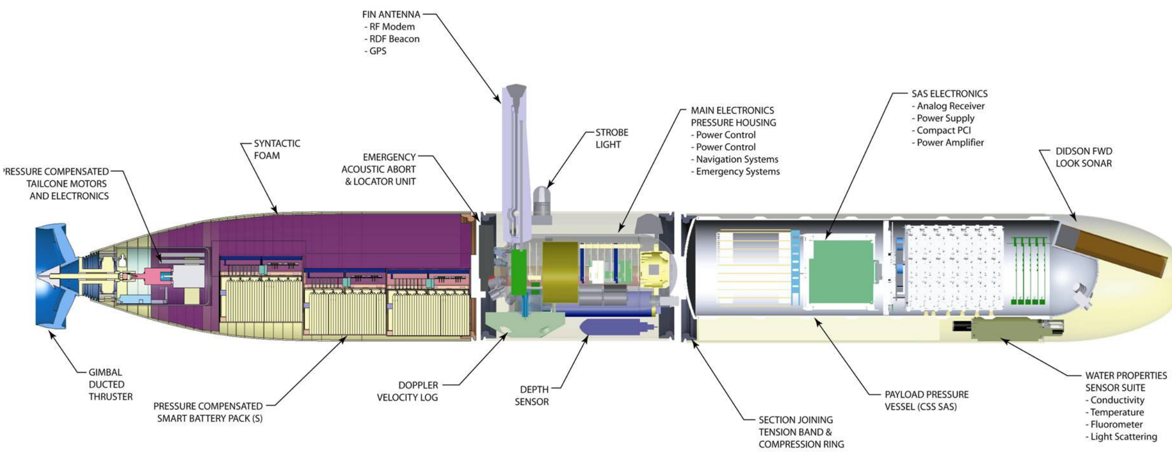

Figure 1: The Bluefin12 modular UUV shown with the Search-Classify-Map underwater mine-countermeasures payload module. Back to front we find the following subsystems: The Propulsion module with thruster and actuators, as well as the electronics and firmware required for control and communication; The Energy module with the rechargeable and removable pressure-tolerant battery packs; The Core modular section with the main vehicle computer, navigation, guidance, and control instrumentation, various core vehicle sensors, communications equipment, and vehicle safety systems; The payload module where we integrate sensor suites developed by outside partners.

The general characteristics of the vehicle can be summarized as follows:

Architecture

- Lightweight Torpedo form factor.
- Flooded, modular, stressed skin exoskeleton made of engineering plastic.
- Pressure tolerant or one-atmosphere dry subsystems placed inside.
- Combination of pressure-balanced oil filled and molded cable interconnects with high reliability connectors.
- Scalable Energy section.
- Accepts multiple, field-reconfigurable payload modules.

Propulsion and actuation

- Ducted, fully actuated propulsor with stators.
- DC brushless motors.
- Single stage planetary gearbox.
- RPM servo.
- Pressure balanced oil filled design.
- Fast, accurate, low latency actuation.
- High efficiency.
- RS-485 multidrop communication.

Energy

- Up to 4.0 kWh.
- Rechargeable.
- Pressure tolerant.
- Up to 12h endurance.
- RS-485 multidrop communication.
- Multiply redundant protection.

Core systems

- PC104 Control computer.
- Navigation and attitude sensors.
- Communication hardware.
- Power distribution and monitoring.
- Fault sensors and safety systems.
- Main electronics housing.
- Launch, localization, and recovery systems.

Dimensions and weight

- 12.75" OD.
- Up to 112" length.
- Up to 300lb weight.

Speed

- 3kts cruise.
- 5kts max.

Depth rating

- 200m.

Payload

- Up to 48" length.
- Up to 150lb weight.

Each of the propulsion, energy, and core (i.e., guidance, control, and navigation) sections are carefully packaged in a compact and highly integrated way across the entire class of Bluefin12 vehicles. Throughout the design process, dynamic performance has been of paramount importance, particularly the sensor selection and tailcone design, as will be discussed later.

Payloads are located forward, physically separate from core systems, and the interface to them is kept as generic and simple as possible to minimize the engineering effort required for their integration. Electrical, mechanical, and software standards ensure that new payloads can be used on any Bluefin12 after they have been integrated for the first time. In addition to the SCM payload suite, a mine identification payload is planned for integration, and the basic platform will be able to carry a number of sensor packages for scientific, military, and security missions.

Vehicle Motion Requirements as a Sonar Platform

As one of the most recent UUV MCM systems now in development, it is instructive to compare the Bluefin12 sensor-imposed vehicle requirements with those of the most advanced existing US Navy minehunting system; the AQS-20x towed minehunting system. The AQS-20x employs a system of real aperture sonars (RAS) in forward, down and side looking sonar configurations (FLS, DLS and SLS) as well as a volume search sonar for mines moored high above the bottom and an electro-optical identification device (EOID) for bottom mine identification. The most demanding AQS-20x vehicle steadiness requirements are for the bottom minehunting mode – the same mode for which the shallow water MCM UUVs such as the Bluefin12 are being developed as an alternative capability. To achieve the required high-resolution, high area coverage rate requirements the vehicle must be very steady as it moves along a survey track. This task is made more difficult by the energetic and changing nature of the shallow water environment.

Even with motion compensation, image stabilization and auto-focus algorithms, there are fundamental limits imposed on AQS-20x motions for good sensor performance. For example, the vehicle yaw motions must be small enough to prevent gaps between beams from adjacent SLS ping cycles. Similarly, the vehicle pitch and roll motions must be small enough to prevent gaps for the DLS or Gap-Filler Sonar (GFS). As the primary coverage sensor, the SLS range must be maximized to achieve high ACR. To achieve sufficiently high probabilities of detection and classification with sufficiently low probabilities of false alarms, high resolution images are needed. This leads to sonar geometries that necessarily impose tight vehicle motion steadiness requirements. Such requirements rooted as they are in the physics of the sensor phenomena are applicable to towed and UUV MCM systems alike.

The SAS systems being developed for MCM UUVs are subject to many of the same steadiness issues. While there has been work toward using overlapping phase centers from different pings to compensate for translation and rotation errors, there are fundamental difficulties in differentiating translation errors from rotation errors. Fluctuations in the properties of the medium and the targets can also be limiting factors. The computational resources for real-time execution of comprehensive compensation algorithms is a serious impediment to implementations that handle all of these error sources – not to mention the research resources to develop the algorithms to a mature state. Hence, both RAS and SAS MCM systems require a very high degree of vehicle steadiness for all systems now in development, towed or UUV. The drive for greater sensor range while maintaining MCM resolution is likely to continue to makes it so.

Quantifying the Requirements

Angular vehicle motions, especially yaw rate, present the most difficult steadiness requirements to achieve. The principal disturbances for UUVs are those due to fluid motion caused by surface waves. A commonly-used steadiness metric is the standard deviation of the motion during a survey leg, 1σ values. Yaw rate limits of 0.1 to 0.25°/sec 1σ are typical for high performance (high ACR and high resolution) MCM systems, either RAS or SAS. Limits for pitch and roll angular rates are typically an order of magnitude larger or 1 to 2°/sec 1σ. Angle limits of around 1 to 2° 1σ are typical. As is often the case in design, aggressive minimization of motions in one degree of freedom causes another to become the driver. While the very tight yaw rate limit paces the design, the other angular limits inevitably come into play as yaw rate is minimized.

The translational degrees of freedom (position and velocity) also come into play even though they may initially appear to be less demanding. The altitude-keeping limit (height above the bottom), for example, is typically on the order of 1 ft 1σ -- a seemingly easy requirement. Two things can conspire to make these translational requirements more difficult than initially perceived. First, the wave-induced vertical disturbances can be very strong. Second, aggressive altitude-keeping leads to vehicle pitch rates that exceed the limits. A similar situation exists for track-keeping and yaw rate. Even though the track-keeping requirement may be 3 or 4 ft 1σ, the restrictions on yaw rate can conspire to cause poor track-keeping performance.

All of these 1σ limits are with respect to a mean value that also may have a limit. The most notable of these for SLS systems is the angle between the vehicle centerline heading and the track heading – sometimes referred to as the crab angle or sideslip angle. Due to beam steering and beam width limitations, both RAS and SAS systems are degraded by large sideslip angles. Relatively modest water currents can cause significant sideslip angles for a UUV moving at a few knots. Forward fins can help mitigate this. Design tradeoffs are presented in this paper for the Bluefin12 design. Limits for the mean values for pitch can establish the vehicle ballasting requirements. Typically, mean pitch angles of ±5° are acceptable. Mean roll angle limits are typically not difficult to achieve with nominal ballasting accuracy.

Environmental Requirements

The three dominant environmental requirements are water depth, sea state and water current. For bottom minehunting, the sensors require the vehicle to operate at a specified altitude for optimum sensor performance. Very Shallow Water (VSW) minehunting goes in to depths as shallow as 10 ft. For such shallow water depths, the vehicle operates at mid-depth, operating closer to the bottom than is optimum for sensor performance. Wave-induced fluid motions are very strong when the vehicle operates so close to the surface. Wave conditions are often specified in terms of a sea state number. Typical values for VSW MCM are sea state 2 or 3.

Water currents are another important feature of the shallow water environment. With typical UUV speeds of around 3 knots, water currents of even 1 knot are a very significant issue. Water currents as large as 2 knots are not atypical at some shallow water sites. The sonar sensors are typically configured for a preferred over-the-bottom speed. For a given survey leg, the along-track component of current requires the vehicle to have an increased or decreased water speed. This can become an issue for vehicle endurance. The across-track component of current can become a problem for the sonar sensors. Typical UUVs, with only tail control surfaces, must line up with the relative water velocity vector during non-turning flight. A cross current causes the vehicle to fly with a yaw angle with respect to the track to maintain flight along the survey track, much as an aircraft has to crab when landing in a cross-wind. This will be discussed more quantitatively in subsequent sections.

Vehicle Response to Shallow Water Disturbances

As the vehicle moves through water that is in motion due to surface waves, it responds in a manner similar to that of an aircraft passing through air turbulence. The response of an underwater vehicle is somewhat more complex though. The higher density of water compared to air makes the fluid accelerations an important source of disturbance, not just the fluid velocities as is generally the case in air. Another difference is that the spatial gradients of the velocity and acceleration disturbances are important. For aircraft this is only important in roll disturbances. For underwater vehicles, all of the gradients of velocity and pressure are important. Figure 2 is a sketch of the velocity disturbances encountered by a UUV as it passes through a wave field.

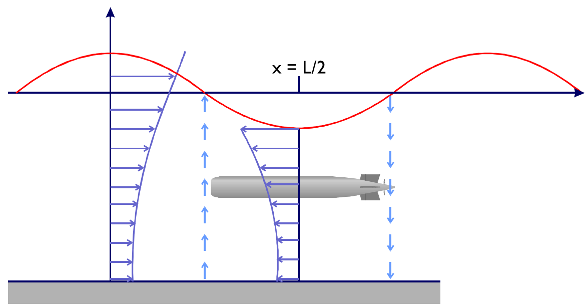

Figure 2 - Fluid motion as a vehicle disturbance.

The vehicle autopilot and control surfaces must work to counter these disturbances. In control system design terminology, this is the disturbance rejection capability of the control system implemented in the autopilot. The control system must also have good command response capability. The design strategy to achieve this is discussed in a later section of this paper. Here, the vehicle disturbance response characteristics are described.

Much of the disturbance rejection design can be accomplished using state space methods for multiple-input, multiple-output systems (MIMO). This part of the design process is based on LTI (linear time-invariant) models of the vehicle at a given speed through the water. Design points at various speeds are evaluated. A speed-scheduled architecture is then used to implement these control system designs in the autopilot. One way to display the vehicle response to the fluid disturbances is in the frequency domain.

Figure 3 shows the vehicle response to a lateral velocity disturbance. These are noted in conventional gust transfer function terminology; e.g. y/vg is offtrack perturbation per v-gust. Both open-loop and closed-loop responses are shown.

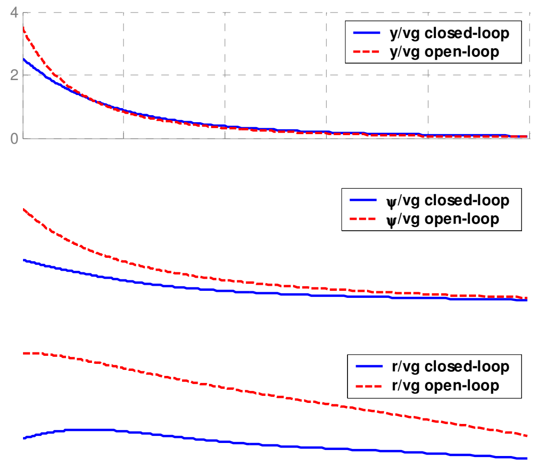

Figure 3 - Bluefin12 closed- and open-loop response to lateral gust (vg); offtrack (y), yaw (ψ) and yaw rate (r).

Some important characteristics can be noted in the three plots in

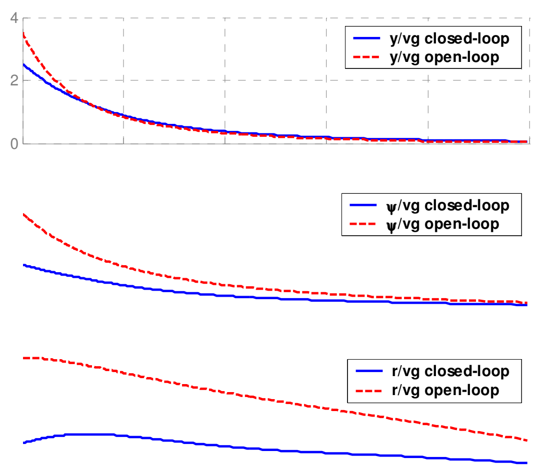

Figure 3. Since yaw rate steadiness is the most difficult requirement, the lower plot is the main design focus. It can be seen that significant reduction in the r/vg response (yaw rate due to lateral gust) is achieved. An example of the frequency range of the disturbance is shown in Figure 4. The frequency of the disturbance depends on the sea state, vehicle speed and heading with respect to the waves. Here, the sea state is 3, vehicle speed 3 knots and a variety of headings with respect to the waves are shown. The energy of the wave disturbance falls within a range of 0.5 to 3 radians/second. That is the range in which we seek the greatest disturbance rejection. For brevity, only the velocity and acceleration spectra (Figure 5) are shown here. The gradient spectra have similar frequency content.

The bottom plot in Figure 3 shows that about a factor of two reduction in yaw rate response to lateral gust is achieved in this control system implementation. The reduction in yaw angle (middle plot) is not quite as much and there is no reduction in offtrack perturbations due to lateral gust. The design has been tilted toward reducing yaw rate response at the expense of offtrack response. Similar characteristics are seen in Figure 5 for vehicle response to fluid acceleration motions.

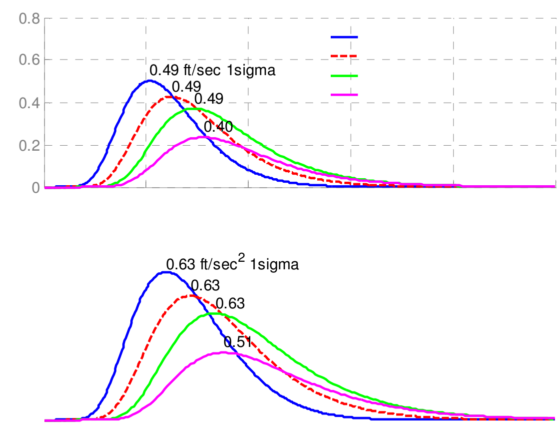

Figure 4 - Example encounter spectra for velocity and acceleration disturbances

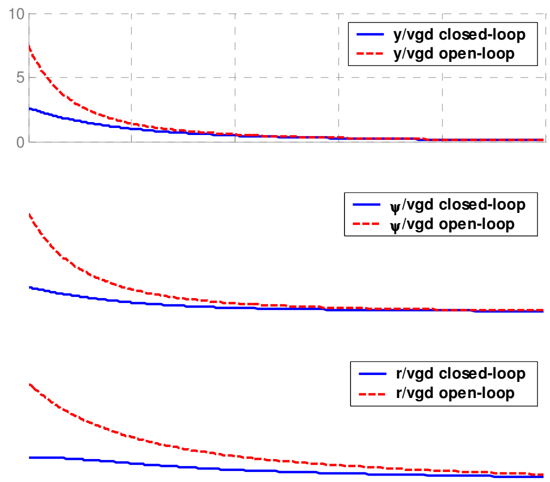

Figure 5 - Bluefin12 closed- and open-loop response to lateral acceleration gust (dvg/dt); offtrack (y), yaw (ψ) and yaw rate (r).

To achieve this disturbance rejection performance, several requirements flow to vehicle systems. This is discussed in the Control Strategy section below.

Vehicle Control in Cross Currents

The vehicle perturbation response to disturbances in but one part of the vehicle control design. While perturbation characteristics are often given primacy in academic control studies, steady state limits and saturation effects are performance-limiting attributes that often are the key design drivers for vehicle control design. One such attribute for the Bluefin12 is the requirement to fly along the survey track without exceeding the maximum allowable sideslip angle – the angle made between the vehicle centerline and the track (Figure 6). Due to beam steering and beam width limitations, SLS systems are degraded by large sideslip angles. Relatively modest water currents can cause significant sideslip angles for a UUV moving at a few knots.

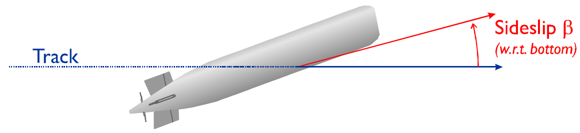

Figure 6 - Diagram of vehicle sideslip angle during track-keeping with a cross current.

Table 1 lists the sideslip angle for a tail-controlled vehicle (no forward fins deflected) for a range of current magnitudes; 0.5, 1 and 2 knots. All cases are for a cross-track current component of 0.5 knots. Cases for running on a track against the current and with the current are shown. When running against the current, the vehicle maintains a constant speed over the bottom of 3 knots. This results in a water speed of nearly 5 knots for the 2 knot current condition. The sideslip angles can be as large as nearly 10°. If the SLS can tolerate no more 5° of sideslip angle, then the vehicle control system must be able to keep the sideslip angle lower than that for the necessary operating conditions. That means that the vehicle control system must be capable of holding a sideslip angle of at least 5°.

	Track direction against current, vehicle constant 3 knots wrt bottom			**Track direction with current, vehicle constant 2.5 knots wrt water**		
Current magnitude	0.5	1.0	2.0	0.5	1.0	2.0
Cross-track component	0.5	0.5	0.5	0.5	0.5	0.5
Speed along track wrt bottom	3.0	3.0	3.0	2.46	3.33	4.40
Speed wrt water	3.04	3.90	4.96	2.5	2.5	2.5
Sideslip angle β	9.46°	7.37°	5.78°	5.68°	5.68°	5.68°

Table 1 - Sideslip angle for different current magnitudes.

Forward control fins can be used to achieve this by producing side force independent of the tail control surfaces. This definitely has major implications for vehicle design but it is the only way to reduce sideslip angle for track-keeping in a cross current. Forward fins are considered here, not thrusters, since thrusters are ineffective for forward speeds above 2 knots[1]. The forward fins must be sized to be able to fly the vehicle straight and level with at least 5° of sideslip. They are arranged in an x-configuration to provide maximum lateral control authority for a given fin and actuator size. The fin size parameters varied here are span (Bte, span at the trailing edge) and chord. The leading edge is swept for a taper ratio of 0.9 and it is a NACA0012 section shape. The key fin sizing tradeoff results are shown in Figure 7. The top plot shows the sideslip angle that can be held as a function of the fin size parameters. To achieve at least 5° of sideslip authority, the span needs to be at least 5.4". For a span of 6", the chord can be 4.5". This is a reasonable fin size for the Bluefin12 vehicle which has a diameter of 12.75".

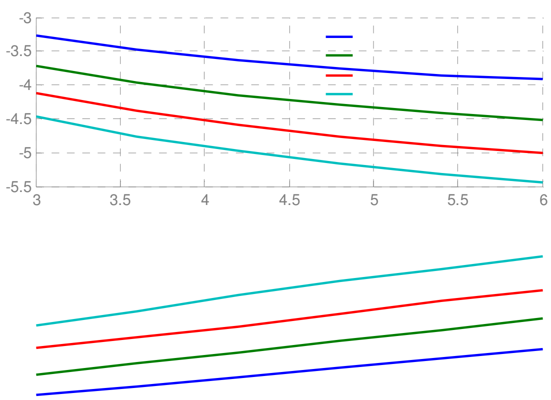

Figure 7 - Forward fin sizing for sideslip control; hydrodynamic sideslip and rudder angles.

There is only small speed loss in this crabbing condition, less than 0.25 knot (Figure 8). The forward fins are also used as ailerons for roll control. The lower plot in Figure 8 shows the aileron deflection angle needed to hold the roll angle to zero.

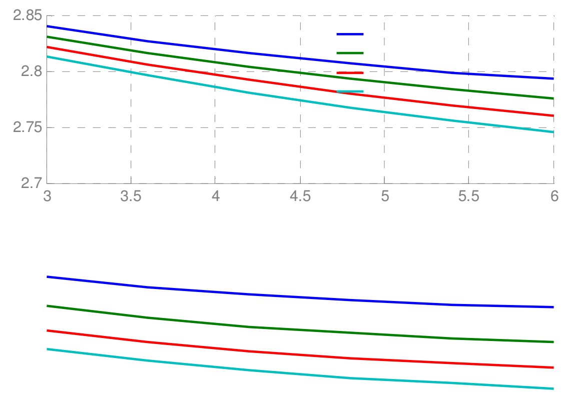

Figure 8 - Forward fin sizing for sideslip control; speed and aileron angle.

Control Strategy

Continuing our focus on two important control performance characteristics, yaw rate disturbance rejection and sideslip control, the track-keeping control design strategy is discussed. Here we focus on control for the configuration with the aft control surfaces only. An important feature of the UUV autopilot control system is the use of a compensator in the yaw rate feedback loop to minimize yaw rate response. The compensator is selected to provide significant disturbance rejection in the frequency band of wave-induced fluid velocity disturbances – 0.5 to 2 radians/second. The effect is to reduce yaw rate motions due to disturbances at the expense of control bandwidth of the outer loops for track-keeping.

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[1] "UUV Controllability at Transition Speeds: Thruster and Fin Control Authority Requirements", K. W. Watkinson, N. S. Smith, D. E. Humphreys, 9th International Symposium on Unmanned Untethered Submersible Techhnology, Sept. 1995

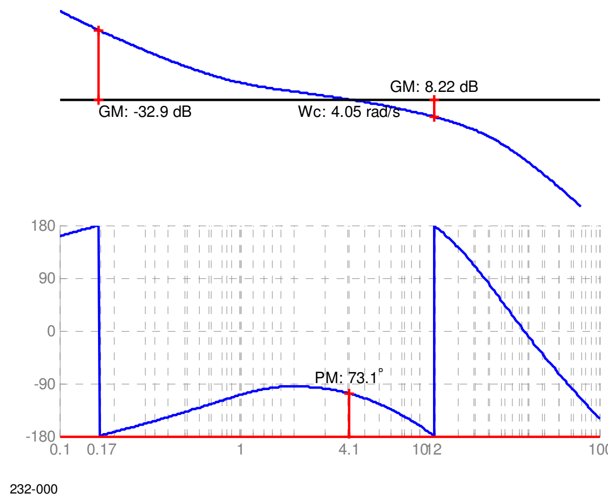

Figure 9 - Bode diagram showing stability margins for the Bluefin12 AOSAS UUV; rudder (δr) loop break

Figure 9 shows the Bode diagram for the rudder loop break. This is the applicable loop for assessing yaw rate feedback. The height of the magnitude curve in the disturbance bandwidth is a key feature. The compensator has been selected to raise this as high as possible without driving the phase and gain margins too low. Note that the crossover frequency ω_c is over 4 radians/seconds. This must be somewhat higher than the disturbance frequency. A high ω_c results in higher actuator bandwidth and autopilot update rate requirements and lower latency. These requirements have been set at

- 4 Hz minimum actuator bandwidth
- 20 Hz minimum autopilot update rate
- 50ms maximum autopilot latency

As already mentioned, in order to minimize the yaw rate disturbance response, it is also necessary to reduce the bandwidth of the outer track-keeping loops. The bandwidth (ω_c) of the heading and off-track loops are shown in Figure 10 and Figure 11. The off-track loop is made to be quite sluggish indeed, with a bandwidth of only 0.179 radians/second. From a guidance and control point of view, it would be better if this were much higher – say around 0.5 radians/second. From the SAS sensor perspective, though, this sluggish response is a good trade-off. It permits strong disturbance rejection for yaw rate motions.

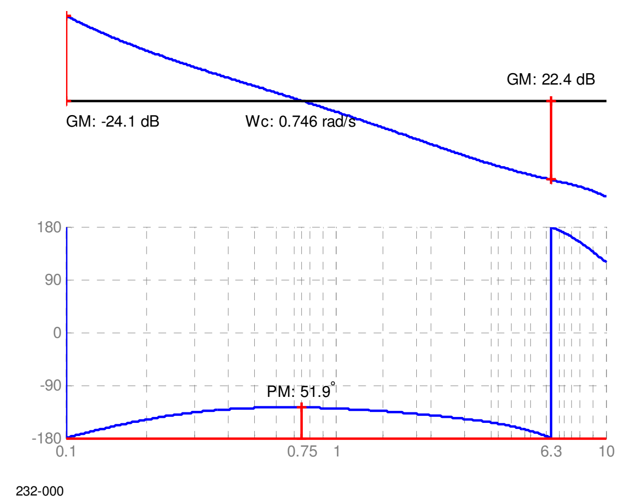

Figure 10 Bode diagram showing stability margins for the Bluefin12 AOSAS UUV; heading (ψ) loop break

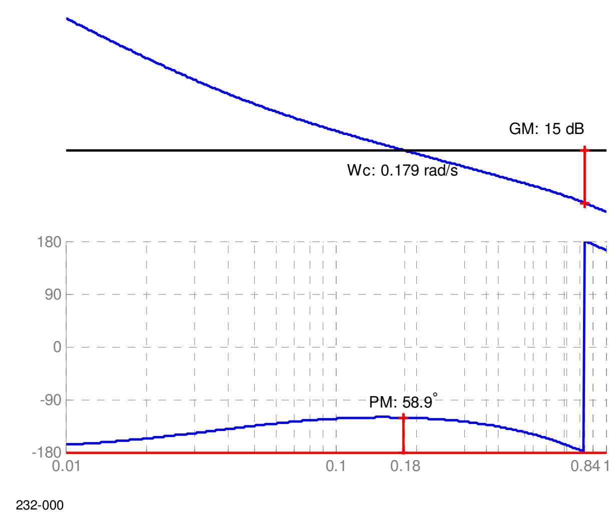

Figure 11 Bode diagram Bluefin12 AOSAS UUV; off-track (y) loop

Implementation of Vehicle Requirements

Fortunately, many of the desired traits for vehicle dynamic control coincide with manufacturing, logistical, and other design requirements. For example, there are structural, operational, and manufacturing advantages as well as dynamic performance benefits in keeping the overall length reasonable, the shells intact with a minimum of cutouts and appendages, neutral buoyancy, etc. Therefore, most of the impact of the analysis above was felt in two areas; the tailcone design and the selection of a control/navigation sensor suite.

Tailcone mechanical design

Our experience with the actuated, ducted, propulsor concept for Bluefin21 has always been very good, and we wanted Bluefin12 to employ the same principle. Like its larger brother, it sports a 3-bladed propeller located in a duct that is supported by 8 stators. Compared to the existing design, the center of lift is forward, closer to the pivot such that the actuator torque requirements are minimized. Also, the duct diameter has been maximized within the 12.75" envelope to give it maximum control authority and reduce uncertainties in inflow patterns. All elements are optimized for propulsive efficiency, and the resulting package features a large lifting surface in a small envelope, inherent shaft torque neutralization, and immunity to impacts during rough weather recovery.

The entire subassembly is now packaged in a single, pressure balanced oil filled housing, as shown in Figure 12. The internal actuator mechanism drives the thruster mechanism in the horizontal and vertical degrees of freedom through a sequence of gears, avoiding the need for linkages or actuator mixing.

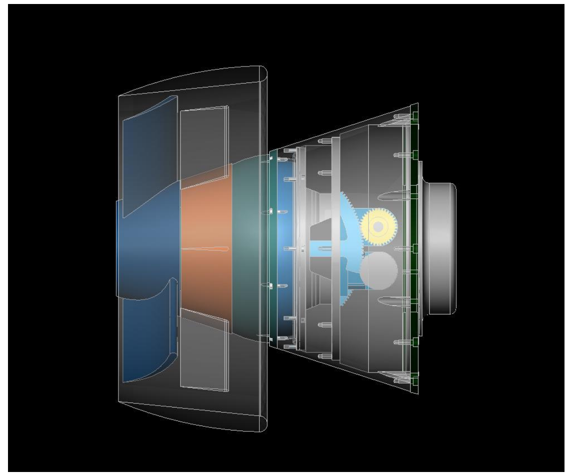

Figure 12: The tailcone is packaged in a single oil filled housing.

The mechanical design emphasizes compact packaging, robustness and reliability, ease of assembly and service, and clean hydrodynamics. Much effort was expended to achieve ±15° range of motion, thus ensuring a very tight vehicle turn radius of 1 vehicle length or better.

Tailcone actuators and thruster

The actuators are based on DC brushless motors as these are very efficient and provide reliable, non-mechanical, position feedback based on the hall-effect signal used for commutation. The feedback is incremental however, so a homing step between two limit sensors is required upon power-up.

The maximum actuator torque requirement was based on the hydrodynamic force of the stator-duct combination. We stipulated that the actuator should be able to drive the tailcone through hydrodynamic stall at the maximum cruise speed, 2.5m/s. This requirement supersedes the torque derived from the small amplitude bandwidth specifications.

With this value for output torque, experimental result for internal viscous oil drag , and the basic electric motor equations, we could perform the design trade-offs for actuator motor size, gear ratio, maximum current draw, and efficiency.

The actuator position control loop is closed internally with PID, and has been verified on a bench top prototype of the tailcone mechanism. A typical move is shown in Figure 13. We observe a slight overshoot and a complete move in less than 300ms. The final gear ratio will be higher but slew rate is still faster than required.

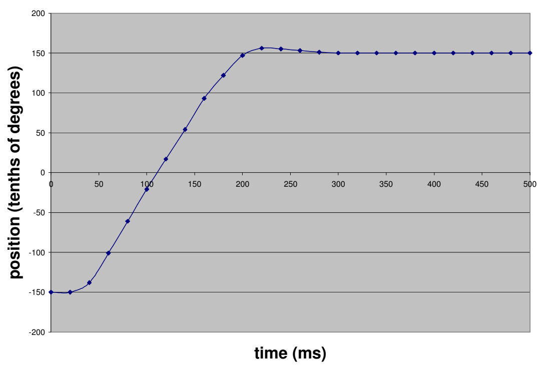

Figure 13: Actuator move from one extreme to the other.

Bench top testing has shown that repeatability of calibration and subsequent motion is better than 0.1°, so the accuracy of the final product will depend largely on how well mechanical backlash can be controlled.

Thruster gearmotor selection was performed in a similar fashion, and thruster RPM is also closed loop controlled. The speed scheduled PID controller can maintain shaft speeds from 20 to 500RPM with 1% accuracy.

Tailcone electronics and communication

The tailcone communication and internal control is based on small PIC and PAL microcontrollers and discrete power components. All circuit design and firmware developments were performed in-house. The three boards that control the motors have as much commonality as possible, and the same is true for the RPM and position control logic. All power switching takes place at 40kHz to keep acoustic noise out of the most sensitive frequency bands for other systems, but it can be reprogrammed should the need arise. The three circuits are individually addressable on a 19200 Baud, multi-drop, RS485 serial bus and the command set is kept compact yet human readable to support the 20Hz update rate. The update rate is limited by the microcontrollers' ability to service serial traffic, which again is a function of how efficiently the PID loop is executed. The firmware has been carefully implemented to support the specified update and latency, but further development in this area may permit a higher communications rate yet.

Commands to the tailcone represent values for angles and RPM in real-world units. If the tailcone detects an internal fault condition, its firmware can latch into the "off" state until the fault is acknowledged from the controlling computer. The conditions that could cause a fault are over-temperature, water leaks, loss of oil compensation, and Hall sensor failures. In addition, the actuators have over-current protection which saves the hardware in case of jamming.

Attitude, depth, and velocity reference

Sensor selection is crucial to vehicle steadiness performance as well as navigation accuracy. Noise, bias, and drift can all conspire to degrade dynamic performance.

The sensor suite is centered around a tactical grade inertial measurement unit. Its biases are better than 1mg / 4°/h and the noise level better than 0.3°/√h. Initial testing has confirmed these performance metrics. The IMU output is oversampled, averaged, and blended with the digital compass output, using an algorithm developed by VCT, to give the best estimates for rates and attitude.

Vehicle depth is sensed by a high precision digital pressure sensor (0.01%FS), based on a floating piezoresisitive transducer. Thermal shock can sometimes be a source of error for depth sensing. This was one of the reasons for locating the sensor in the Main Electronics Housing, with a hydraulic connection to the outside.

The remainder of the navigation sensor suite consists of a 300kHz Doppler Velocity Log aided by a Sound Velocity Sensor for sensing speed over ground and through the water, a WAAS augmented GPS receiver. Future navigation aiding by acoustic ranging and tracking is planned as well.

Concluding Remarks

With prototype sea-trials planned for fall 2003, Bluefin12 promises to make the range and resolution of Synthetic Aperture Sonar available in very shallow water during generous sea state operational windows. We hope and anticipate that the initial tests will show that careful control analysis and design has paid off, resulting an extremely stable platform for this payload.

Acknowledgements

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